# Icarus and Daedalus: conceptual and tactical lessons for marine ecosystem-based management

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**A growing realization that the oceans are being degraded has led to calls for a fundamental shift in the management of activities that affect marine ecosystems. Insights from research in coastal marine ecosystems will help shape policies that consider interactions between ecosystem components. The concept of connections is central to coastal marine ecology. Connections between: (1) ecosystem structure and functioning; (2) land and sea; (3) marine habitats; (4) species; (5) diverse stressors; and (6) knowledge and uncertainty are of particular importance. These linkages provide conceptual and tactical guidance to inform the transition to ecosystem-based management for the oceans. Conceptual guidance includes recognizing of linkages, expecting of surprises, and avoiding hubris in management. Tactical guidance includes managing coastal systems at watershed scales, emphasizing monitoring, using area-based management, and incorporating the recognition of uncertainties into decision-making. Ultimately, successful management of human activities that affect the oceans will require integrating these conceptual and tactical approaches.**

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The first two major commissions to review the status and governance of the oceans in 30 years, the Pew Oceans Commission (POC 2003) and the US Commission on Ocean Policy (USCOP 2004), recently concluded that the oceans are increasingly being affected by human activities and that new approaches to management are needed. Both highlight the importance of moving from the current fragmented system of governance to an ecosystem-based approach to management of these activities (Panel 1).

New information and new syntheses of existing information will be insufficient to fundamentally change the ways in which we manage human activities that affect the marine environment. A change in perspective is also required. The myth of Icarus and Daedalus offers some useful ways to think about the challenges of ecosystem-based management for the oceans (Figure 1). Marine community ecology provides both conceptual and tactical insights that are relevant to a shift to ecosystem-based management. Conceptual lessons can help change the way we think about managing human activities that affect the oceans, encouraging avoidance of Icarus-like hubris. Tactical lessons challenge us to emulate Daedalus' cleverness and point to ways in which we can reform the management of activities that affect marine systems to reflect these changing perspectives.

Ecosystem-based management is fundamentally about perceiving the big picture, recognizing connections, and striving to maintain the elements of ecosystems and the processes that link them. Ecosystem-based management is often misconstrued as the management of an entire ecosystem. More accurately, it is a coordinated effort to manage the diverse human impacts that affect an ecosystem to ensure the sustainability of the ecosystem services it provides. Ecosystem-based management was used in ancient societies, is still used in some non-western cultures (Berkes *et al.* 1998), and has been described in the scientific and management literature for almost a century (Grumbine 1994). Work on the science, policy, and implementation of ecosystem-based management in terrestrial systems has yielded important advances (eg Christensen *et al.* 1996). The application of the same concept to marine systems is more recent and has, to date, been primarily focused on fisheries management (eg EPAP 1999; Babcock and Pikitch 2004; Browman and Stergiou 2004). Evolving from a single-species approach to an ecosystem-based approach in marine fisheries is an important step towards more holistic management.

## In a nutshell:

- The US Commission on Ocean Policy and the Pew Oceans Commission both recommend ecosystem-based management of human activities that affect the oceans
- Insights from coastal marine ecology will be instrumental in structuring ecosystem-based management of marine systems
- Shifts in both conceptual frameworks and tactics are required to implement ecosystem-based management
- Examples of regional programs that are making progress toward ecosystem-based management serve as models and provide evidence of the feasibility of more comprehensive management of human impacts on marine systems

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However, ecosystem-based management of fisheries represents only one component of the larger governance changes needed for the oceans. At this interface between marine science and policy, scientists and managers continue to reshape perspectives and tools for ecosystem-based management. Coastal marine ecology offers many lessons that are timely and relevant for developing these approaches to management (Figure 2).

At the core of ecosystem-based management is the recognition of connections between: (1) ecosystem structure, functioning, and services; (2) land and sea; (3) marine habitats; (4) species; (5) diverse stressors; and (6) knowledge and uncertainty. The lessons learned about these connections in nearshore marine systems can inform the shift towards more ecosystem-based approaches (Table 1). Here, I examine some of the ways in which principles from nearshore marine research can help both the generators and users of ecological science to further integrate the management of human impacts on marine ecosystems by providing examples of ways in which basic research can inform ecosystem-based management. Recognizing that ecological theory, experiments, principles, and tools are important for the management of marine systems is easy. Communicating their utility and ensuring that their influence is brought to bear on real-world problems is not.

**Panel 1. Indications of the status of marine ecosystems and their current governance**

Ecosystem-based management involves streamlining fragmented governance structures to better address the degradation of marine environments.

***Signs of degradation of marine environments:***

- The 2005 National Coastal Condition Report classified only 21% of US estuarine environments as unimpaired; the rest were identified as threatened or impaired for human use and/or aquatic life (EPA 2004).
- In 2003, the National Marine Fisheries Service was able to determine the status of 25% of 932 fish stocks examined. Of these, 38% were classified as experiencing overfishing, were overfished, or both (NMFS 2004).
- The rate of introductions of invasive species to coastal environments has risen exponentially over the past 200 years (Ruiz *et al.* 2000).
- The population density in coastal counties is over five times that of non-coastal counties – and growing. In addition, land is being developed at more than twice the rate of population growth (Beach 2002).

***Signs of fragmented governance of US marine environments:***

- More than 60 congressional committees and subcommittees oversee agencies that manage activities in the marine environment.
- Approximately 20 federal agencies and permanent commissions are charged with implementing marine-related statutes.
- At least 140 federal ocean-related statutes are in force.
- 35 coastal states, commonwealths, and territories are responsible for the management of nearshore waters.

## Connections between ecosystem structure, functioning, and services

The Millennium Ecosystem Assessment (MEA 2005) classifies ecosystem services into four categories: (1) provisioning services that produce goods, such as food and fresh water; (2) regulating services that modulate ecosystem processes, such as disease control and climate regulation; (3) cultural services that provide nonmaterial benefits, such as education and recreation; and (4) supporting services, such as nutrient cycling and primary production, that are necessary for the generation of all other ecosystem services. Marine ecosystems provide all of these services.

The functioning of an ecological system, like all systems, depends on its structure. There is a long history of debate about the functional role of biological diversity in ecosystems: sometimes it results in stability, sometimes instability; sometimes increased productivity, sometimes decreased productivity. Establishing the relative importance of key species compared to diversity per se remains an active area of inquiry. Regardless, we know that the number of species and/or the identities and abundances of species in systems can affect ecosystem properties (Jones *et al.* 1997; Loreau *et al.* 2001). Although most research on this topic has been conducted in terrestrial systems, ecosystem functioning has also been linked to the diversity and structure of marine communities (Stachowicz *et al.* 2002; Worm *et al.* 2002).

Courtesy of Scala/Art Resource, NY

***Figure 1.*** *Daedalus and his son Icarus were captives on the island of Crete. In order to escape, Daedalus made two pairs of wings out of wax and feathers, and warned Icarus not to fly too high. However, Icarus, feeling the power of flight, flew higher and higher. Ultimately, the wax in his wings melted and he plummeted to his death. In this story, Daedalus is not only intelligent and innovative, but also recognizes the limits of his own cleverness. Icarus possesses the tragic fatal flaw of hubris, or too much faith in his own abilities.*

Courtesy of A Guerry, L Ahlgren, B Menge, and M Webster

***Figure 2.*** *Research on coastal systems has formed the basis for much knowledge about the structure and functioning of marine ecosystems. Unlike the deep sea and open ocean, intertidal and shallow subtidal systems are relatively accessible and are therefore amenable to experimentation and long-term monitoring. Lessons from coastal systems therefore have the potential to inform ecosystem-based management for the oceans.*

Humans have altered the structure and functioning of the earth's ecosystems in far-reaching and dramatic ways (MEA 2005). One of the essential contributions of the field of ecology will be to help shape a future in which humans and the natural systems on which they depend can sustainably coexist (Palmer *et al.* 2005). Economic arguments for conservation that incorporate ecosystem services suggest that the benefit to cost ratio of an effective global conservation program is approximately equal to or greater than 100:1 (Balmford *et al.* 2002).

Both conceptual and tactical guidance can be gained from the connections between ecosystem structure, functioning, and services. The increasing realization that human activities have the potential to compromise marine ecosystem services provides an impetus for shifting to a more holistic, ecosystem-based approach to managing human activities. Because the provisioning of goods and services depends on ecosystem functioning, which in turn depends on ecosystem structure, careful attention to maintaining both the components of systems and the processes that link them is essential.

Tactically, insights from ecological theory, case studies of coupled social–ecological systems, and work on indicators of ecosystem properties are useful as management becomes more integrative. Current theoretical work, such as the study of complex adaptive systems, is synthetic in nature and can reveal emergent properties of systems (Levin 1999). Case studies of coupled social–ecological systems are yielding important insights into such key ecosystem properties as multiple stable states and resilience (eg Elmqvist *et al.* 2003). One of the challenges to implementing marine ecosystem-based management is the identification of indicators with which to assess the state of ecosystems and the effectiveness of management, though progress has been made (Link 2002). For example, the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) uses selected prey populations that play key roles in the ecosystem and predator populations that are likely to be responsive to changes in prey availability as indicators of ecosystem performance (Agnew 1997).

## Connections between land and sea

Human activities on land can have major impacts on marine systems. When more than 10% of a watershed is converted to impervious surfaces such as roads and rooftops, the water quality of associated aquatic systems is degraded (Beach 2002). More than 60% of the coastal rivers and bays in the continental US are moderately to severely degraded by nutrient pollution as a result of terrestrial-based, human-driven changes in nutrient cycling (Howarth *et al.* 2000). Human-derived sources of nitrogen (including wastewater, agricultural fertilizers, and fossil-fuel combustion) have increased nitrogen fluxes into the coastal waters of the northeastern US six- to eightfold (Howarth *et al.* 2000). Alterations of nutrient availability have been shown to stimulate phytoplankton growth; the development of hypoxia and anoxia; changes in the biomass and community composition of phytoplankton, macroalgae, and invertebrates; increases in the frequency of toxic algal blooms; and more subtle effects such as the alteration of growth and reproductive rates of invertebrates and changes in the seasonality of productivity (Cloern 2001). Pollution is not the only link between actions on land and conditions offshore. Changes in seawater temperature, potential harbingers of ocean warming through anthropogenic climate change, have been shown to cause dramatic shifts in marine benthic communities (Schiel *et al.* 2004). However, the most well-known examples of the land–sea connection are hypoxic areas, the so-called "dead zones" that occur as a result of increased nutrient loading from growing human populations, agriculture, and food and energy consumption (Rabalais *et al.* 2002).

Bays are particularly instructive for understanding the linkages between land and sea. Their proximity to land and distinct geographical boundaries create tight feedbacks, causing bays to be heavily impacted by human activities but also providing practical opportunities for holistic management. Tampa Bay, FL, and the

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**Table 1. Lessons learned from nearshore marine systems that can help inform ecosystem-based approaches in the oceans**

| *Connection* | *Lessons* | *Conceptual guidance* | *Tactical guidance* |
|---|---|---|---|
| 1. Ecosystem structure, functioning, and services | • provisioning of goods and services depends upon ecosystem functioning<br>• ecosystem functioning depends on ecosystem structure | • provides the foundation for shifting from a single-species to an ecosystem-based approach<br>• strive to maintain the parts of ecological systems and the processes that link them | • research the connections between structure, functioning and services, particularly with a focus on maintaining services<br>• tighten linkages between systems theory and application to management |
| 2. Land and sea | • actions on land can have important ramifications for coastal marine ecosystems<br>• coastal systems can be resilient | • think big: be cognizant of linkages<br>• scales of management should be matched with scales of systems | • manage coastal oceans and bays at a watershed scale<br>• link terrestrial and marine conservation efforts<br>• emphasize monitoring of the status and trends of coastal systems, and impacts of human activities on them |
| 3. Marine environments | • organisms, energy, and nutrients flow between habitats<br>• the pelagic environment plays an important role in determining community structure of the benthos | • recognize the importance of context<br>• acknowledge the uniqueness of places | • identify and protect key habitats, such as nurseries<br>• consider the juxtaposition of of marine habitats in conservation strategies<br>• use regional management |
| 4. Species | • species are embedded in complex communities<br>• indirect effects of species interactions can cause unexpected consequences<br>• effects of perturbations can be delayed | • expect surprises<br>• take precautions<br>• expect time-lags<br>• recognize the impossibility of managing each piece of a system in isolation<br>• keep all the players to maintain the natural range of interaction | • monitor<br>• research conditions under which different interaction types are likely to play key roles<br>• use marine protected areas and marine reserves |
| 5. Diverse stressors | • no stressor operates in a vacuum | • consider how stresses interact in natural systems<br>• take precautions | • research cumulative effects of stressors<br>• manage multiple stressors in tandem |
| 6. Knowledge and uncertainty | • marine ecosystems are complex; there are significant uncertainties in their future states | • avoid hubris<br>• do not expect precise predictions of future states | • be explicit about uncertainties; incorporate them into decision making; develop probable scenarios<br>• use insurance policies<br>• manage for resilience |

Chesapeake Bay provide prime examples of these linkages (both the generation and mitigation of human impacts). In the 1970s, the Hillsborough Bay section of Tampa Bay exhibited numerous symptoms of nutrient pollution. Efficient treatment of municipal wastes and the abatement of pollution at agricultural fertilizer production plants in the early 1980s decreased the annual wastewater loading of total nitrogen tenfold, halved chlorophyll levels and turbidity, decreased noxious blooms of cyanobacteria, and allowed for the recolonization of seagrasses and their associated communities (Pribble *et al.* 2003). Land-use changes, overfishing, the introduction of exotic species, and other factors have combined to greatly diminish oyster and seagrass populations and water quality in the Chesapeake Bay (Boesch and Greer 2003; CBP 2004).

There has been some progress towards managing bays within an ecosystem framework. The Tampa Bay Estuary Program has continued to improve water quality by addressing non-point source pollution in the watersheds that drain to the bay (Pribble *et al.* 2003). Emphasis on the connection between land and sea, monitoring, data management, and adaptive management have been essential to this success. The Chesapeake Bay Program is also guided by the need to mitigate diverse human impacts (Figure 3). Although significant challenges remain, increases in migratory fish habitat, declining phosphorous and nitrogen loads, and increases in streamside forests are a few indicators of

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***Figure 3.*** *Residential development along the Chesapeake Bay shoreline. Development and other land-use activities in surrounding watersheds can have major impacts on nearshore ecosystems; recognition of these kinds of land–sea linkages is an important component of marine ecosystem-based management.*

progress toward restoration (CBP 2004). The Scientific and Technical Committee of the Chesapeake Bay has modeled the outcomes of various scenarios of land use and development, forest management, agriculture, and fisheries within Chesapeake Bay watersheds (Boesch and Greer 2003). The integration and synthesis of these factors exemplifies the ecosystem-based approach.

There is both conceptual and tactical guidance to be gained from this connection between land and sea. On the conceptual side, recognition of the large-scale connections between marine and terrestrial systems will lead to management that better matches the scales at which ecological systems operate. Management structures and scientific disciplines often treat upland and coastal areas as separate systems. Overcoming these distinctions and recognizing the links between the two is an important component of ecosystem-based management. On the tactical side, land–sea connections highlight the importance of: (1) managing coastal oceans and bays at watershed scales; (2) linking marine and terrestrial conservation efforts; and (3) monitoring the status of coastal systems. Focusing ecosystem-based management on one geographical area, such as a bay, has the advantage of highlighting the human impacts that require consideration, thereby making a broad concept like ecosystem-based management more feasible.

## Connections among marine environments

Marine environments are connected by the flow of organisms, energy, and nutrients. Many marine species use different habitats at different stages in their lifecycles. Most benthic invertebrates in the rocky intertidal zone have pelagic larvae, while seagrass beds, mangrove forests (Figure 4), and other coastal wetlands frequently serve as nursery areas for juveniles of many species whose adults reside elsewhere. Carbon subsidies from sub-tidal kelps are important determinants of the structure of intertidal communities and growth rates of organisms within them (Duggins *et al.* 1989; Bustamante *et al.* 1995). Given the movement of organisms and resources between systems, what happens in one habitat will probably affect neighboring systems.

The larger oceanographic context in which habitats are embedded provides the mechanism by which connectivity of marine environments occurs and plays an important role in structuring ecological communities. Nearshore oceanographic features influence recruitment, competition, predation, and resource supply (Menge 2003). Thus, the community dynamics of one patch of habitat, such as a rocky reef, may be quite different from those of another, similar patch. Understanding the oceanographic context of a particular region helps in tailoring management to that area. For instance, some sites may produce relatively more larvae, owing to local oceanographic conditions, and could therefore serve as larval sources for nearby areas (Leslie 2004). Although the determination of sources and sinks has proven difficult in many marine systems, genetic techniques (Sotka *et al.* 2004) and mapping of habitat patches and surface currents can yield information about the connectivity of marine habitats (Roberts 1997). A better understanding of the flow of materials between these habitats, and the spatial scales most appropriate for thinking about particular systems, are key areas of ongoing research.

Conceptually, connections among marine environments highlight the importance of context and the recognition of the uniqueness of places. Tactically, the flow of organisms, energy, and resources indicates that conserving mosaics of habitat types linked by larval dispersal and other processes will be an important facet of effective management. Although guidelines at the national scale will be necessary, regional input and flexibility are essential. This echoes the recommendation of both the USCOP (2004) and POC (2003), calling for enhanced regional coordination.

## Interspecific connections

There are at least three different types of connections between species that can inform ecosystem-based man-

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*Figure 4. Mangroves serve an important role in connecting the land and sea, mediating nutrient and energy exchange between these environments. They also serve an important role in connecting different marine habitats, such as providing habitat for juveniles of some coral-reef fish as well as feeding grounds for adults.*

agement: (1) top predators and other species in the community; (2) weak connections among species; and (3) indirect interactions between species.

In communities with keystone predators such as sea otters and some sea stars, one species can have an extraordinary impact on the rest of the community (eg Paine 1966; Estes and Palmisano 1974). Maintenance of keystone species is therefore an important component of a systems perspective. In an ocean where top predators have been fished to 10% of their pre-industrial levels (Myers and Worm 2003), and where coastal systems have been drastically altered by the top-down effects of fisheries (Jackson *et al.* 2001), it is important to consider the ecosystem-wide effects of the removal of top predators.

Intermediate-sized consumers and weak interactions may also play important roles in structuring marine communities (Sala and Graham 2002; Neutel *et al.* 2002). Berlow (1999) showed that species which have the weakest average interaction strengths (the per capita effect of one species on another) also tend to have the greatest variability in those strengths. Similarly, Harley (2003) showed that the interaction strength between two species in one context explained only 37% of the variation in the interaction strength between those species in another context. Therefore, a species that is not important to community dynamics at one point in time or space may be very important at a different time or place.

A number of different kinds of indirect effects can be critical in shaping communities (Wootton 1994). Menge (1995) showed that, on average, in rocky intertidal communities, indirect effects accounted for approximately 40% of the changes in species abundances observed after experimental removals. In some situations, the effects of a perturbation on a community can be predicted with reasonable success (Menge 2003). However, in other cases, indirect effects can cause disturbances to have unexpected consequences over both short and long timeframes (Peterson *et al.* 2003). Given the complexity of communities and the prevalence of indirect effects, we should not expect particular actions or disturbances to have simple effects.

Area-based management, including the creation of marine reserves and other types of marine protected areas, can be used to address the challenge of managing systems in the face of interspecific connections. Marine protected areas are regions of the ocean where destructive and/or extractive activities are limited; marine reserves, also called no-take areas, are regions where all extractive and destructive activities are prohibited. Marine protected areas can be valuable tools for ecosystem-based management because their use stems from the goal of protecting entire systems rather than managing individual parts. Such areas allow complicated interactions between species to play out in relatively intact systems. Reserves can also serve as reference points from which we can learn about human impacts (Castilla 1999), and if they maintain the full complement of species and their interactions, they can also act as insurance against management failures in other areas (NRC 2001). However, marine protected areas are not a panacea. They are often small, so that attention to management actions in the broader matrix in which they are embedded is essential, as is flexibility for adaptation. Just as with any other management tool, they should be employed in conjunction with monitoring programs.

Conceptually, connections between species highlight the importance of expecting surprises (eg indirect effects); taking precautions (because it is impossible to predict all indirect effects); recognizing the impossibility of managing each piece of a system in isolation; and striving to maintain all the components of a system. Tactically, these lessons emphasize the importance of setting management targets with built-in buffers, monitoring over long time frames, continuing research efforts to better understand where and when different types of interactions are important, and considering the use of area-based management.

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## Connections among diverse stressors

Our understanding of the effects of stressors on biological systems comes, predominantely, from laboratory examinations of individual stressors on particular species. In nature, no stressor operates in isolation, but the importance of context and the synergistic effects of stressors are not well understood. One area of research that has been explored is the connection between disease and other stressors. For example, both increased nutrient concentrations and increased temperatures have been linked to disease severity and susceptibility in Gorgonian sea fans and reef-building corals (Cerrano *et al.* 2000; Bruno *et al.* 2003).

The degradation of the Black Sea provides a striking example of a system impacted by the synergistic effects of multiple stressors and the need for ecosystem-based management. In the past three decades, the effects of eutrophication, oil pollution, over-fishing, inadequate coastal zone management, and the invasion of the exotic ctenophore, *Mnemiopsis leidyi*, have combined to cause a dramatic shift to a profoundly different phytoplankton community, frequent outbreaks of *Mnemiopsis*, and the collapse of commercial fish stocks such as anchovy, sprat, and horse mackerel (BSEP 1999; Rass 1992). Although some attempts are being made to address these stressors in an ecosystem context, the political and economic climate in many of the countries bordering the Black Sea compound the challenges of restoration (Acar 2001).

On the conceptual side, the potential for stressors to interact highlights the importance of recognizing multiple stressors such as pollution and climate change and of taking precautions in their management. In a tactical sense, the connections between diverse stressors not only underline the importance of examining multiple stressors in the laboratory, but also the need to examine cumulative impacts on ecological systems and to manage multiple stressors in tandem. An ecosystem-based approach makes this possible. For example, the POC recommendations for a watershed-based approach to managing coastal development and non-point source pollution are based on taking the broad view rather than looking at each development project and each pollutant in isolation (POC 2003). The Chesapeake Bay and Tampa Bay Programs provide examples of attempts to manage multiple stressors in tandem.

## Connections between knowledge and uncertainty

We know a lot about community structure and functioning at fine scales (ie those of 1-$m^2$ quadrats) and at coarse scales (ie general themes describing the way things work), but precise predictions of specific outcomes are difficult in complex ecological systems. In general, an emphasis on precise predictions reflects a reductionist view that is inappropriate for complex systems. A more reasonable framework describes possible scenarios, often with attached probabilities. This approach reflects a more synthetic view, is more appropriate for complex systems, and can provide useful guidance for decision-making.

Allison *et al.* (2003) recognized the linkage between knowledge and uncertainty in their analysis of marine reserve design under various disturbance regimes. They acknowledged that severe disturbances such as hurricanes and oil spills are common across long temporal and large spatial scales. They used the frequency of past catastrophic events to calculate "insurance factors", the extent to which the size of a marine reserve would need to be increased in order to achieve the desired objectives. Essentially, they were planning for resilience in the face of inevitable disturbances. This kind of thinking is also applicable when establishing acceptable levels of pollutants and other stressors. Using scientific knowledge to predict probable outcomes of particular actions and then adding an insurance factor may be a useful way to approach marine policy.

Another tactic for explicitly incorporating uncertainty into decision-making is the use of Bayes' theorem in decision analysis to examine the potential outcomes of a decision based on uncertainty and knowledge of past events (Ellison 1996). Bayesian inference has been successfully used in fisheries management (eg Punt and Hilborn 1997; McAllister and Kirchner 2002), but further work on this interface between scientific uncertainty and decision making is needed. More generally, the incorporation and communication of uncertainty is essential to science-based decision-making (Kinzig *et al.* 2003).

The connection between knowledge and uncertainty is instructive; although we have a long history of attempting to manage ecological systems to look a certain way or to produce a particular level of resources, we have had limited success. Even if such efforts had been more successful in the short term, stasis may not be optimal in the long term. Because the reduction of natural variability through management for stasis can create a less resilient system, external perturbations are more likely to result in drastic changes in ecosystem states (Holling and Meffe 1996). Thus, even if management for precise endpoints were feasible, striving to retain the natural ranges of variation in ecological systems appears to be a better long-term strategy in order to avoid catastrophic shifts (Holling and Meffe 1996; Folke *et al.* 2002). Ecosystem-based management incorporates the idea of managing with environmental variability in mind. Recognizing uncertainty in management endeavors is an important step, but recognizing the certainty of variability at multiple spatial and temporal scales is essential to the maintenance of functioning systems.

From a conceptual standpoint, the recognition of uncertainty instructs us to avoid hubris by recognizing the limits of our understanding of ecological systems and our ability to manage them. From a tactical standpoint, the limits of our knowledge about complex ecological systems underscore the importance of incorporating uncertainties into decision-making processes, using insurance policies in management activities, and managing for resilience, rather than for desired endpoints.


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## Progress towards ecosystem-based management of marine systems

The concept of ecosystem-based management provides an overarching goal of integrated management of human activities that affect the oceans and represents one end of a spectrum from piecemeal to holistic management.

Dramatic declines in cod and bluefin tuna provide well-known examples of social and ecological failures of single-species fisheries management (Pauly and Maclean 2003). Precipitous declines in species such as sea turtles, that are primarily taken as by-catch in fisheries targeting other species, also provide evidence that a piecemeal approach to management has not worked (NRC 1990). In some respects, substantial progress towards ecosystem-based management of fisheries has occurred, including requirements to identify essential fish habitat within fishery management plans, and the inclusion of language relevant to an ecosystem-based approach in key policy documents such as the Magnuson-Stevens Fishery Conservation and Management Act. Nevertheless, fisheries management often continues to focus on single species.

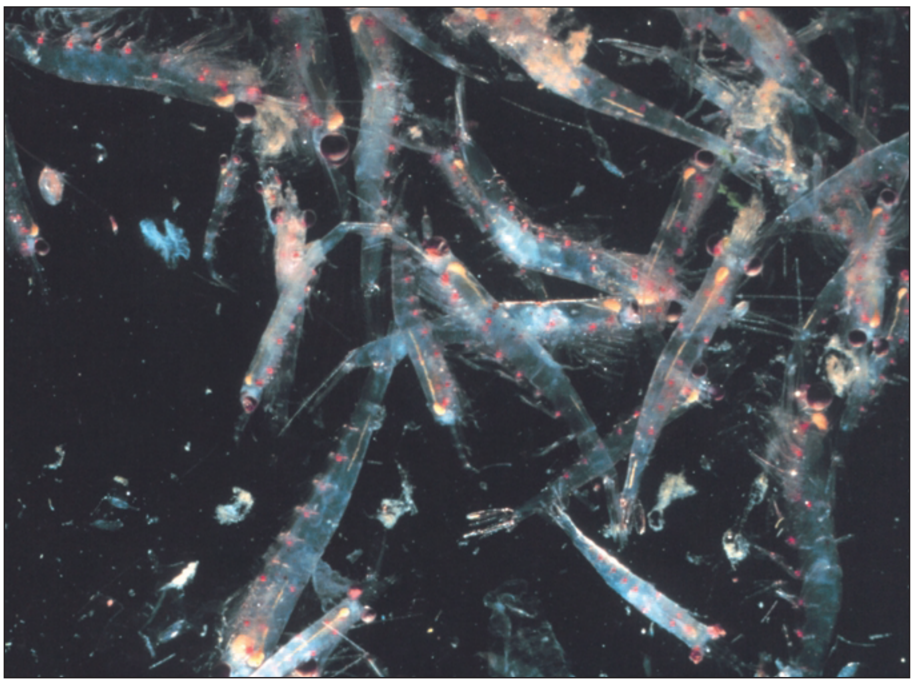
One example of a more comprehensive approach to fisheries is provided by the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR). CCAMLR's approach is fundamentally ecosystem-based; it was developed to prevent over-exploitation of Antarctic krill (Figure 5), which was considered essential to the recovery of over-fished whale and seal populations (Constable *et al.* 2000). By setting catch limits for krill at a higher level than would be set for single-species management, CCAMLR aims to allow krill populations to recover to levels that will support their predators (Constable *et al.* 2000). CCAMLR's ecosystem-based approach to fisheries management also involves taking precautions. For example, recognizing that "reactive management (the practice of taking management action when the need for it has become apparent) is not a viable long-term strategy for the krill fishery" (CCAMLR, cited in Constable *et al.* 2000), CCAMLR has incorporated the connections between ecosystem structure and functioning, species, and knowledge and uncertainty into their management framework.

While CCAMLR's approach is a pioneering attempt at ecosystem-based fishery management, fishing is the only human impact that is managed. The South Florida Ecosystem Restoration Task Force (SFERTF) is a congressionally mandated effort to coordinate the restoration of the 47 000 km$^2$ South Florida ecosystem by addressing a diversity of human impacts. In this historically mismanaged system of uplands, wetlands, and coral reefs, restoration efforts are founded upon three primary goals: (1) restoring hydrology and water quality; (2) restoring, preserving, and protecting natural habitats and species; and (3) fostering compatibility of management activities (SFERTF 2000). These goals exemplify an ecosystem-based approach to managing human impacts on an entire region.

## Conclusions

Scientists, managers, decision makers, and stakeholders of marine resources are beginning to realize that although some components of marine systems are well understood, it is impossible to manage each piece of an ecological system in isolation. Too much faith in the feasibility of managing individual components yields complicated, fragmented, sometimes contradictory, and often bewildering regulations, an inability to achieve management targets and, most importantly, damage to ecosystems. Ecosystem-based management provides a recourse from the trap of trying to manage each piece until the whole is managed. Key elements of ecosystem-based management include recognizing the intrinsic limits to our current – and potential – understanding of and ability to manipulate ecosystems, the profound impacts of human activities on marine systems, and an attendant requirement to take precautions when managing diverse human impacts.

Ecosystem-based management requires a shift in the philosophy of governance. Lessons from research in



Courtesy J Hall/NOAA

***Figure 5.*** *An understanding of the crucial role of krill in Antarctic foodwebs informs an ecosystem-based approach to fishery management in the southern polar oceans.*

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coastal marine systems remind us to recognize connections, to expect surprises, and to take precautions. They also emphasize the importance of striving to maintain the full range of components and processes within systems in order to maintain the full range of ecological interactions, of aiming for resilience rather than for desired endpoints, and, overall, of avoiding hubris by recognizing our own limitations. Tactically, this translates into managing at ecologically relevant scales such as watersheds, monitoring the status and trends of systems over long time periods, and incorporating marine protected areas and marine reserves into management frameworks. These connections also highlight the importance of incorporating uncertainties into decision making, using insurance policies, and enhancing our understanding of marine systems in order to better understand the effects of human actions. Ultimately, better management of human activities that affect the oceans will require a combination of both cleverness and humility.

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## References

Acar S. 2001. Regional Reporting for the Intergovernmental Review of the GPA 2001. Black Sea Environmental Program-Project Implementation Unit. http://www.gpa.unep.org/igr/Reports/BLACKSEA.htm. Viewed 22 Feb 2005.

Allison GW, Gaines SD, Lubchenco J, and Possingham HP. 2003. Ensuring persistence of marine reserves: catastrophes require adopting an insurance factor. *Ecol Appl* **13**: S8–S24.

Agnew DJ. 1997. The CCAMLR ecosystem monitoring programme. *Antarc Sci* **9**: 235–42.

Babcock EA and Pikitch EK. 2004. Can we reach agreement on a standardized approach to ecosystem-based fishery management? *B Mar Sci* **74**: 685–92.

Balmford A, Bruner A, Cooper P, *et al.* 2002. Economic reasons for conserving wild nature. *Science* **297**: 950–53.

Beach D. 2002. Coastal sprawl: the effects of urban design on aquatic ecosystems in the United States. Arlington, VA: Pew Oceans Commission.

Berkes F, Kislalioglu M, Folke C, and Gadgil M. 1998. Exploring the basic ecological unit: ecosystem-like concepts in traditional societies. *Ecosystems* **1**: 409–15.

Berlow EL. 1999. Strong effects of weak interactions in ecological communities. *Nature* **398**: 330–34.

Boesch DF and Greer J. 2003. Chesapeake futures: choices for the 21st century. Edgewater, MD: Chesapeake Research Consortium.

Browman HI and Stergiou KI (eds). 2004. Perspectives on ecosystem-based approaches to the management of marine resources. *Mar Ecol–Prog Ser* **274**: 269–303.

Bruno JF, Petes LE, Harvell CD, and Hettinger A. 2003. Nutrient enrichment can increase the severity of coral diseases. *Ecol Lett* **6**: 1056–61.

Bustamante RH, Branch GM, and Eekhout S. 1995. Maintenance of an exceptional intertidal grazer biomass in South Africa: subsidy by subtidal kelps. *Ecology* **76**: 2314–29.

BSEP (Black Sea Environmental Program) 1999. Black Sea transboundary diagnostic analysis. Programme Coordinating Unit, Global Environmental Facility Black Sea Environmental Programme. http://www.grid.unep.ch/bsein/tda/index.htm. Viewed 22 Feb 2005.

Castilla JC. 1999. Coastal marine communities: trends and perspectives from human-exclusion experiments. *Trends Ecol Evol* **14**: 280–83.

CBP (Chesapeake Bay Program). 2004. The state of the Chesapeake Bay; a report to the citizens of the bay region. Report CBP/TRS 273/05 EPA 903-R-04-009.

Cerrano C, Bavestrello G, Bianchi CN, *et al.* 2000. A catastrophic mass-mortality episode of gorgonians and other organisms in the Ligurian Sea (Northwestern Mediterranean), summer 1999. *Ecol Lett* **3**: 284–93.

Christensen NL, Bartuska AM, Brown JH, *et al.* 1996. The report of the Ecological Society of America committee on the scientific basis for ecosystem management. *Ecol Appl* **6**: 665–91.

Cloern J. 2001. Our evolving conceptual model of the coastal eutrophication problem. *Mar Ecol–Progr Ser* **210**: 223–53.

Constable AJ, de la Mare WK, Agnew DJ, *et al.* 2000. Managing fisheries to conserve the Antarctic marine ecosystem: practical implementation of the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR). *ICES J Mar Sci* **57**: 778–91.

Duggins DO, Simenstad CA, and Estes JA. 1989. Magnification of secondary production by kelp detritus in coastal marine ecosystems. *Science* **245**: 170–73.

Ellison AM. 1996. An introduction to Bayesian inference for ecological research and environmental decision-making. *Ecol Appl* **6**: 1036–46.

Elmqvist T, Folke C, Nystrom M, *et al.* 2003. Response diversity, ecosystem change, and resilience. *Front Ecol Environ* **1**: 488–94.

EPA 2004. National coastal condition report II. Washington, DC: Office of Research and Development/Office of Water. Report EPA-620/R-03/002.

EPAP (Ecosystem Principles Advisory Panel). 1999. Ecosystem-based fisheries management: a report to Congress by the Ecosystem Principles Advisory Panel. Silver Spring, MD: National Marine Fisheries Service, NOAA.

Estes JA and Palmisano JF. 1974. Sea otters: their role in structuring nearshore communities. *Science* **185**: 1058–60.

Folke C, Carpenter S, Elmquist T, *et al*, 2002. Resilience and sustainable development: building adaptive capacity in a world of transformations. *Ambio* **31**: 437–40.

Grumbine RE. 1994. What is ecosystem management. *Conserv Biol* **8**: 27–38.

Harley CDG. 2003. Species importance and context: spatial and temporal variation in species interactions. In: Kareiva P and Levin SA (Eds). The importance of species; perspectives on expendability and triage. Princeton, NJ: Princeton University Press.

Holling C and Meffe G. 1996. Command and control and the pathology of natural resource management. *Conserv Biol* **10**: 328–37.

Howarth R, Anderson D, Cloern J, *et al.* 2000. Nutrient pollution of coastal rivers, bays, and seas. *Issues in Ecology* **7**. Washington, DC: Ecological Society of America.

Jackson JBC, Kirby MX, Berger WH, *et al.* Historical overfishing and the recent collapse of coastal ecosystems. *Science* **293**: 629–63.

Jones CG, Lawton JH, and Shachak M. 1997. Positive and negative effects of organisms as physical ecosystem engineers. *Ecology* **78**: 1946–57.

Kinzig A, Starrett D, Arrow K, *et al.* 2003. Coping with uncer-

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tainty: a call for a new science–policy forum. *Ambio* **32**: 330–35.
Leslie H. 2004. Advancing marine reserve science: from field experiments to marine conservation planning tools (PhD dissertation). Corvallis, OR: Oregon State University.
Levin S. 1999. Fragile dominion: complexity and the commons. Reading, MA: Perseus Books.
Link JS, Brodziak JKT, Edwards, SF, *et al*. 2002. Marine ecosystem assessment in a fisheries management context. *Can J Fish and Aquat Sci* **59**: 1429–40.
Loreau M, Naeem S, Inchausti P, *et al*. 2001. Biodiversity and ecosystem functioning: current knowledge and future challenges. *Science* **294**: 804–08.
McAllister M and Kirchner C. 2002. Accounting for structural uncertainty to facilitate precautionary fishery management: illustration with Namibian orange roughy. *B Mar Sci* **70**: 499–540.
MEA (Millenium Ecosystem Assesssment). 2005. The Millennium Ecosystem Assessment Synthesis report. www.millennium assessment.org/en/Products.Synthesis.aspx. Viewed 14 Apr 2005.
Menge BA 2003. The overriding importance of environmental context in determining the consequences of species deletion experiments. In: Levin SA (Ed). The importance of species: perspectives on expendability and triage. Princeton, NJ: Princeton University Press.
Menge BA. 1995. Indirect effects in marine rocky intertidal interaction webs: patterns and importance. *Ecol Mon* **65**: 21–74.
Myers RA and Worm B. 2003. Rapid worldwide depletion of predatory fish communities. *Nature* **423**: 280–83.
Neutel AM, Heesterbeek JAP, de Ruiter PC. 2002. Stability in real food webs: weak links in long loops. *Science* **296**: 1120–23.
NMFS (National Marine Fisheries Service) 2004. Annual report to Congress on the status of US Fisheries – 2003. Silver Spring, MD: US Dept Commerce, NOAA.
NRC (National Research Council) 1990. Decline of sea turtles: causes and prevention. Washington, DC: National Academy Press.
NRC (National Research Council). 2001. Marine protected areas: tools for sustaining ocean ecosystems. Washington, DC: National Academy Press.
Paine RT. 1966. Food web complexity and species diversity. *Am Nat* **100**: 65–75.
Palmer M, Bernhardt ES, Chornesky EA, *et al*. 2005. Ecological science and sustainability for the 21st century. *Front Ecol Environ* 2005: 4–11.
Pauly D and Maclean J. 2002. In a perfect ocean: the state of fisheries and ecosystems in the North Atlantic Ocean. Washington, DC: Island Press.
Peterson CH, Rice SD, Short JW, *et al*. 2003. Long-term ecosystem response to the Exxon Valdez oil spill. *Science* **302**: 2082–86.
POC (Pew Oceans Commission) 2003. America's living oceans: charting a course for sea change. A report to the nation. Arlington, VA: Pew Oceans Commission.
Pribble JR, Janicki AJ, and Greening H. 2003. Baywide environmental monitoring report, 1998–2001. Tampa Bay, FL: Tampa Bay Estuary Program. Report 06-02.
Punt AE and Hilborn R. 1997. Fisheries stock assessment and decision analysis: the Bayesian approach. *Rev Fish Biol Fisher* **7**: 35–63.
Rabalais NN, Turner RE, and Wiseman WJ Jr. 2002. Gulf of Mexico hypoxia, aka "the dead zone." *Annu Rev Ecol Syst* **33**: 235–63.
Rass TS. 1992. Changes in the fish resources of the Black Sea. *Oceanology* **32**: 197–203.
Roberts C. 1997. Connectivity and management of Caribbean coral reefs. *Science* **278**: 1454–57.
Ruiz GM, Fofonoff PW, Carlton JT, *et al*. 2000. Invasion of coastal marine communities in North America: apparent patterns, processes, and biases. *Annu Rev Ecol Syst* **31**: 481–531.
Sala E and Graham MH. 2002. Community-wide distribution of predator–prey interaction strength in kelp forests. *PNAS* **99**: 3678–83.
Schiel DR, Steinbeck JR, and Foster MS. 2004. Ten years of induced ocean warming causes comprehensive changes in marine benthic communities. *Ecology* **84**: 1833–39.
SFERTF (South Florida Ecosystem Restoration Task Force) 2000. Coordinating success: strategy for restoration of the South Florida ecosystem. www.sfrestore.org/documents/isp/sfweb/sfindex.htm. Viewed 22 Feb 2005.
Sotka E, Wares JP, Barth JA, *et al*. 2004. Strong genetic clines and geographical variation in gene flow in the rocky intertidal barnacle *Balanus glandula*. *Mol Ecol* **13**: 2143–56.
Stachowicz JJ, Fried H, Osman RW, and Whitlatch RB. 2002. Biodiversity, invasion resistance, and marine ecosystem function: reconciling pattern and process. *Ecology* **83**: 2575–90.
USCOP (US Commission on Ocean Policy) 2004. An ocean blueprint for the 21st century. Final report. Washington, DC.
Wootton JT. 1994. The nature and consequences of indirect effects in ecological communities. *Annu Rev Ecol Syst* **25**: 443–66.
Worm B, Lotze HK, Hillebrand H, and Sommer U. 2002. Consumer versus resource control of species diversity and ecosystem functioning. *Nature* **417**: 848–51.

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